RESEARCH PAPER

An Overview of Self-Healing Concrete Technologies Using Recycled Aggregate

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ABSTRACT

One of the most popular building materials is concrete, but it is prone to cracking, which lowers durability and raises maintenance expenses. Self-healing concrete is a cutting-edge technique that can fix cracks on its own, prolonging the life of buildings. By lowering building waste and preserving natural resources, this method promotes sustainability when paired with recycled aggregates. An overview of self-healing concrete made from recycled aggregates is given in this study, along with information on its mechanics, techniques, benefits, drawbacks, and potential.

Keywords: Self-healing concrete, recycled aggregate, sustainable construction, crack repair, durability, green materials.

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I. Introduction

Its strength, durability, and adaptability, concrete is the most often used building material worldwide. However, it is naturally vulnerable to cracking due to things like shrinkage, temperature changes, mechanical loads, and exposure to the environment. Even tiny fractures like this can let gasses, chemicals, and water in, which over time can cause structural damage and corrosion of the reinforcement. Such damage can shorten a structure's service life and necessitate substantial financial resources for maintenance and repair. In contemporary civil engineering, the idea of self-healing concrete has surfaced as a novel and sustainable solution to these problems.

Self-healing concrete is a kind of smart material that can fix cracks on its own without help from outside sources. This healing can be achieved by artificial methods including bacterial healing, encapsulated healing agents, and vascular networks, or by natural processes like the ongoing hydration of unreacted cement particles (autogenous healing). These processes enhance long-term durability, lessen permeability, and restore the material's integrity.

Concurrently, recycled aggregates made from building and demolition debris are being used because to the growing need for sustainable construction methods. Incorporating recycled aggregates into concrete lessens environmental contamination while simultaneously reducing the use of natural resources. Recycled aggregates can improve internal curing and aid in the self-healing process, even though their porous nature may have an impact on mechanical qualities.

This study aims to explore the integration of self-healing technology with recycled aggregate concrete. The objectives include studying the fundamental concept of self-healing concrete, evaluating the role and influence of recycled aggregates, and analysing the healing efficiency and durability performance of such materials. Additionally, the research seeks to identify the advantages and limitations associated with this approach, including economic and structural considerations. Finally, it aims to explore future research opportunities to enhance performance, reduce costs, and enable large-scale implementation. Through this comprehensive overview, the study contributes to the development of sustainable and resilient construction materials.

II. Literature Review

Mehta, P. K., and Monteiro, P. J. M. (2014), in their book *Concrete: Microstructure, Properties, and Materials*, provide a comprehensive understanding of the fundamental behavior of concrete at the microstructural level. The authors explain how the properties of concrete are largely governed by the interactions between cement paste, aggregates, and the interfacial transition zone (ITZ). They emphasize that factors such as porosity, permeability, and microcracking significantly influence the strength and durability of concrete. The book highlights the importance of proper material selection and mixes design in achieving desired performance characteristics. It also discusses the role of supplementary cementitious materials and curing conditions in enhancing durability. Although not focused exclusively on recycled aggregates or self-healing concrete, the principles outlined in this work are highly relevant. The understanding of microstructure and hydration processes forms the basis for developing advanced materials like self-healing concrete and optimizing the use of recycled aggregates in sustainable construction.

- **Singh.B et al. (2015)**, the authors investigated the utilization of recycled aggregates in concrete as a sustainable alternative to natural aggregates. The study focused on evaluating the mechanical and durability properties of recycled aggregate concrete (RAC). The authors observed that recycled aggregates, obtained from construction and demolition waste, exhibit higher water absorption and lower density due to the presence of adhered mortar. This affects the workability and compressive strength of concrete. However, the research highlighted that with proper mix design and partial replacement levels, satisfactory strength and performance can be achieved. The study also emphasized that recycled aggregates contribute to environmental sustainability by reducing landfill waste and conserving natural resources. Furthermore, it was noted that RAC shows improved internal curing, which may enhance durability under certain conditions. Overall, the findings support the feasibility of using recycled aggregates in concrete for both structural and non-structural applications, provided appropriate quality control measures are implemented.
- **Construction and Building Materials(2026),** have explored the use of recycled aggregates and self-healing mechanisms in concrete, providing valuable insights into material performance and sustainability. These studies commonly report that recycled aggregates, when properly processed and graded, can replace a significant portion of natural aggregates without severely compromising mechanical properties, although workability and strength typically decrease with higher replacement levels. Research also highlights that recycled aggregate concrete exhibits higher porosity and water absorption, which negatively affects durability under aggressive environments but can enhance internal curing beneficial for healing processes. In terms of self-healing, articles in the journal demonstrate that incorporating bacteria, mineral additives, or encapsulated healing agents can effectively reduce crack widths and improve impermeability, leading to enhanced long-term durability. Coupled with recycled aggregates, these techniques show potential for sustainable, resilient concrete systems, though optimal mix designs and practical implementation strategies remain active areas of investigation. Overall, the literature supports combining recycled aggregates with engineered healing mechanisms to balance performance and environmental benefits.
- The **American Concrete Institute (ACI)** has produced several influential committee reports and technical publications that provide guidance on sustainable concrete practices, including the use of recycled materials in concrete construction. An important document in this field is **ACI 130R-19: *Sustainable Concrete Construction Materials Report***, which outlines sustainable strategies for concrete production, including material choices, recycled/reused aggregates, and the role of supplementary cementitious materials to reduce environmental impacts. This report emphasizes the need for sustainable material selection and mix design to enhance long-term performance while minimizing resource consumption and carbon footprint. In addition, **ACI Committee 555** has compiled *SP-334: Sustainable Concrete with Beneficial Byproducts*, which focuses on the use of recycled and waste materials—such as recycled concrete aggregates, shredded tire rubber, reclaimed asphalt, and other byproducts—to improve eco-efficiency without compromising concrete performance. It demonstrates how incorporating these recycled constituents can reduce waste, promote circular economy practices, and maintain acceptable mechanical and durability properties. Other ACI resources, including **ACI PRC-130-19: *Report on the Role of Materials in Sustainable Concrete Construction***, further outline strategies for integrating recycled materials and minimizing environmental impact throughout the concrete lifecycle. These reports serve as foundational references for researchers and practitioners aiming to design sustainable concrete systems that balance performance, durability, and ecological responsibility.
- The **Indian Standards (IS) Codes for Concrete Design and Sustainability** provide the regulatory framework and technical guidelines essential for the safe and durable use of concrete in construction across India. Key standards such as **IS 456:2000 – Plain and Reinforced Concrete Code of Practice** lay down provisions for concrete mix design, material specifications, structural detailing, and durability considerations. They emphasize appropriate selection of materials, minimum cement content, cover requirements, and exposure-related design criteria to

ensure long service life and resistance to environmental degradation.

In addition, sustainability-oriented codes like **IS 10262** (Guidelines for concrete mix design) and relevant Bureau of Indian Standards documents encourage the use of supplementary cementitious materials (SCMs) such as fly ash, slag, and pozzolans to reduce embodied energy and greenhouse gas emissions. Although traditional IS codes do not directly address advanced innovations like recycled aggregates or self-healing concrete, they provide the foundational principles—such as strength, durability, and serviceability—that guide research and practical adoption of sustainable materials. These standards serve as benchmarks against which emerging technologies (e.g., recycled aggregate incorporation and self-healing mechanisms) can be evaluated for compliance, safety, and performance, facilitating integration into mainstream construction practice while maintaining quality and durability.

III. Objectives

- To study the concept of self-healing concrete
- To evaluate the role of recycled aggregates
- To analyse healing efficiency and durability
- To identify advantages and limitations
- To explore future research opportunities

IV. Research Methodology

- Collection of secondary data from journals and publications
- Comparative analysis of conventional and self-healing concrete
- Experimental review of crack healing techniques
- Evaluation of mechanical and durability properties

V. The Concept of Self-Healing Concrete

Self-healing concrete is an innovative construction material designed to automatically repair cracks that develop during its service life. Conventional concrete, despite its widespread use and high compressive strength, is inherently brittle and prone to cracking due to factors such as shrinkage, thermal stresses, mechanical loading, and environmental exposure. These cracks, even when very small, can allow the ingress of water, oxygen, and harmful chemicals, which may lead to corrosion of reinforcement and gradual deterioration of the structure. To overcome these limitations and enhance durability, the concept of self-healing concrete has been developed as a smart and sustainable solution.

The fundamental idea behind self-healing concrete is inspired by biological systems, where living organisms can heal wounds naturally. Similarly, self-healing concrete possesses the ability to seal or repair cracks without the need for external intervention. This property not only extends the service life of structures but also reduces maintenance costs and improves safety. The healing process in concrete can occur either naturally or through engineered techniques, broadly classified into autogenous and autonomous healing mechanisms.

Autogenous healing is the natural ability of concrete to heal its own cracks. This occurs due to the continued hydration of unreacted cement particles and the precipitation of calcium carbonate within the cracks. When water enters the cracks, it reacts with calcium hydroxide present in the cement matrix, forming calcium carbonate crystals that gradually seal the cracks. This type of healing is most effective for very small cracks, typically less than 0.2 mm in width. Although autogenous healing is a beneficial property, its effectiveness is limited and cannot fully address larger or more complex cracks.

To overcome the limitations of natural healing, autonomous self-healing techniques have been developed. One of the most widely studied methods is bacterial self-healing concrete. In this approach, specific types of bacteria, such as *Bacillus* species, are incorporated into the concrete mix along with nutrients. These bacteria remain dormant in the concrete until cracks form and water enters. Upon activation, the bacteria metabolize the nutrients and produce calcium carbonate as a byproduct, which fills and seals the cracks. This method has shown promising results in improving durability and reducing permeability.

Another important approach is the use of **encapsulated healing agents**. In this technique, materials such as polymers, adhesives, or mineral-based agents are enclosed within microcapsules or hollow fibers embedded in the concrete. When cracks develop, these capsules rupture and release the healing agent into the damaged area, where it reacts and hardens, effectively sealing the crack. This method allows for targeted and efficient crack repair, even for relatively larger cracks.

Vascular self-healing systems represent a more advanced approach, inspired by the human circulatory system. In this system, a network of channels or tubes is embedded within the concrete, carrying healing agents throughout the structure. When cracks occur, the healing agents are transported to the damaged area through these channels, enabling continuous and repeated healing. Although highly effective, this method is complex and currently limited to experimental applications.

The concept of self-healing concrete offers several significant benefits. It enhances the durability and longevity of structures by preventing the ingress of harmful substances, thereby reducing the risk of corrosion and deterioration. It also minimizes the need for frequent inspections and repairs, leading to cost savings over the life cycle of the structure. Furthermore, it contributes to sustainability by reducing material consumption, energy use, and carbon emissions associated with maintenance and reconstruction. However, despite its advantages, self-healing concrete also faces certain challenges. The initial cost of incorporating healing agents or bacteria can be relatively high compared to conventional concrete. Additionally, there is a lack of standardized design procedures and guidelines for its implementation in large-scale projects. The long-term performance and reliability of some self-healing techniques under varying environmental conditions also require further investigation.

Self-healing concrete represents a transformative advancement in construction technology, offering a proactive approach to managing structural damage. By integrating biological, chemical, and material science principles, it provides a durable and sustainable solution to one of the most persistent problems in concrete structures—cracking. With ongoing research and technological improvements, self-healing concrete has the potential to become a mainstream material in the construction industry, contributing to the development of resilient and long-lasting infrastructure.

VI. The Role of Recycled Aggregates

Recycled aggregates play a crucial role in modern construction practices, particularly in the development of sustainable and eco-friendly materials such as self-healing concrete. Aggregates, which constitute approximately 60–75% of the total volume of concrete, significantly influence its mechanical properties, durability, and overall performance. Traditionally, natural aggregates such as gravel and crushed stone have been extensively used in concrete production. However, the rapid growth of the construction industry has led to the depletion of natural resources and an increase in construction and demolition waste. This has necessitated the adoption of recycled aggregates as a viable alternative.

Recycled aggregates are obtained from processed construction and demolition waste, including old concrete, masonry, asphalt, and other building materials. These materials are crushed, cleaned, and graded to produce aggregates that can be reused in new construction projects. The use of recycled aggregates not only helps in reducing the demand for natural resources but also addresses the environmental challenges associated with waste disposal and landfill accumulation.

One of the key roles of recycled aggregates in concrete is promoting sustainability. By reusing materials that would otherwise be discarded, recycled aggregates contribute to the conservation of natural resources and reduction of environmental pollution. This aligns with the principles of green construction and circular economy, where waste materials are reintegrated into the production cycle. Additionally, the use of recycled aggregates reduces energy consumption and carbon emissions associated with the extraction and transportation of natural aggregates.

In the context of self-healing concrete, recycled aggregates offer unique advantages due to their physical and chemical characteristics. Recycled aggregates typically have higher porosity and water absorption capacity compared to natural aggregates. While this may be considered a disadvantage in conventional concrete, it can be beneficial for self-healing applications. The increased porosity allows recycled aggregates to retain water, which can later be released into the concrete matrix, promoting internal curing. This internal moisture availability supports continued hydration of unreacted cement particles and enhances the autogenous healing process. Furthermore, recycled aggregates can act as reservoirs for healing agents in advanced self-healing systems. Their porous structure can store bacteria, nutrients, or chemical healing agents, which are activated when cracks form and water enter the concrete. This enhances the efficiency of autonomous healing mechanisms, making recycled aggregates a valuable component in smart concrete technologies.

Despite these advantages, the use of recycled aggregates also presents certain challenges. One of the primary concerns is the reduction in mechanical strength. Recycled aggregates often contain remnants of old mortar attached to their surface, which weakens the bond between the aggregate and the new cement matrix. This can result in lower compressive strength and reduced stiffness compared to concrete made with natural aggregates. Additionally, the variability in the quality and composition of recycled aggregates can lead to inconsistent performance, making it difficult to achieve uniform results. Another challenge is the higher water absorption of recycled aggregates, which can affect the workability and water-cement ratio of the concrete mix. Proper mix design and pre-treatment of recycled aggregates, such as pre-soaking or surface treatment, are necessary to mitigate these issues and ensure optimal performance. Advances in processing techniques and quality control measures are helping to improve the reliability of recycled aggregates in construction applications.

The role of recycled aggregates extends beyond technical performance to economic and social benefits. Their use can reduce construction costs, particularly in regions where natural aggregates are scarce or expensive. Additionally, the recycling industry creates employment opportunities and promotes responsible waste management practices. Governments and regulatory bodies are increasingly encouraging the use of recycled materials through policies, standards, and incentives, further supporting their adoption.

Recycled aggregates play a vital role in the transition towards sustainable construction. While they present certain challenges, their environmental, economic, and functional benefits make them an attractive alternative to natural aggregates. In the context of self-healing concrete, their unique properties can enhance healing efficiency and contribute to the development of durable and resilient structures. With continued research, improved processing methods, and standardized guidelines, recycled aggregates are expected to become an integral component of future construction practices.

VII. Types of Recycled Aggregates

Recycled aggregates are derived from construction and demolition waste and are increasingly used as sustainable alternatives to natural aggregates in concrete production. Their classification depends on the source material, composition, and processing method. Understanding the different types of recycled aggregates is essential for determining their suitability in various construction applications, particularly in advanced materials such as self-healing concrete. Each type exhibits distinct physical, mechanical, and chemical properties that influence the performance of concrete.

1. Recycled Concrete Aggregate (RCA)

Recycled Concrete Aggregate (RCA) is the most commonly used type of recycled aggregate. It is obtained by crushing demolished concrete structures such as buildings, bridges, pavements, and other infrastructure. RCA typically consists of natural aggregates coated with residual cement mortar. One of the defining characteristics of RCA is its rough and porous surface due to the presence of adhered mortar. This increases water absorption and reduces density compared to natural aggregates. While this may negatively impact strength and workability, it can be advantageous in self-healing concrete by providing internal curing through moisture retention. RCA is widely used in structural and non-structural concrete applications, road base layers, and pavement construction. With proper processing and quality control, it can partially or fully replace natural aggregates in many applications.

2. Recycled Masonry Aggregate (RMA)

Recycled Masonry Aggregate (RMA) is derived from masonry waste such as bricks, tiles, and ceramic materials. This type of aggregate is generally lighter and more porous than RCA, as masonry materials tend to have lower density and higher water absorption. RMA is primarily used in non-structural applications such as lightweight concrete, masonry blocks, and filling materials. Due to its relatively lower strength and higher variability, it is less suitable for high-strength structural concrete. However, in self-healing systems, its porosity can aid in storing water and healing agents, enhancing crack repair mechanisms. The use of RMA also contributes to reducing landfill waste, particularly in regions with significant brick and ceramic construction debris.

3. Mixed Recycled Aggregate (MRA)

Mixed Recycled Aggregate (MRA) is obtained from a combination of different construction and demolition wastes, including concrete, masonry, asphalt, and sometimes glass or metals. Due to its heterogeneous composition, MRA exhibits variable properties depending on the proportion of each material. The main advantage of MRA is its availability and cost-effectiveness, as it utilizes a wide range of waste materials. However, its inconsistent quality can pose challenges in achieving uniform concrete performance. Proper sorting, processing, and grading are essential to improve its reliability. MRA is often used in road construction, sub-base layers, and non-structural concrete applications. Its use in structural concrete requires strict quality control measures.

4. Recycled Asphalt Aggregate (RAA)

Recycled Asphalt Aggregate (RAA) is obtained from reclaimed asphalt pavement (RAP), which is generated during the rehabilitation or removal of existing roads. This type of aggregate contains asphalt-coated particles, which influence its bonding characteristics. RAA is primarily used in road construction and asphalt mixtures rather than in conventional cement concrete. However, research is exploring its potential use in hybrid concrete systems. The presence of bitumen can reduce water absorption and improve flexibility, but it may also interfere with cement hydration. Although not commonly used in self-healing concrete, RAA represents an important category of recycled aggregate in sustainable infrastructure development.

5. Recycled Glass Aggregate (RGA)

Recycled Glass Aggregate (RGA) is produced by crushing waste glass into fine or coarse particles. It is increasingly being used as a partial replacement for natural sand or fine aggregate in concrete. RGA offers several benefits, including improved aesthetic appearance and reduced landfill waste. However, its use requires careful consideration due to the risk of alkali-silica reaction (ASR), which can cause expansion and cracking in concrete. Proper treatment and the use of supplementary cementitious materials can mitigate these risks. In self-healing concrete, finely ground glass can enhance pozzolanic activity, contributing to improved durability and potential crack-sealing properties.

6. Recycled Plastic Aggregate (RPA)

Recycled Plastic Aggregate (RPA) is derived from waste plastics such as polyethylene terephthalate (PET), polyethylene (PE), and polypropylene (PP). These materials are processed into small particles or fibers and used as lightweight aggregates. RPA is known for its low density, durability, and resistance to moisture. It is commonly used in lightweight concrete, insulation materials, and non-structural components. However, its low stiffness and poor bonding with cement paste can reduce the overall strength of concrete. In the context of self-healing concrete, plastic aggregates can be used to encapsulate healing agents or create voids for storing bacteria and nutrients, contributing to autonomous healing mechanisms.

7. Recycled Ceramic Aggregate (RCA - Ceramic)

Recycled Ceramic Aggregate is obtained from waste ceramic products such as tiles, sanitary ware, and porcelain. These materials are crushed and processed into usable aggregate sizes.

Ceramic aggregates are generally hard and durable but may exhibit higher brittleness and water absorption. They are suitable for use in decorative concrete, paving blocks, and certain structural applications when properly processed. Their porous nature can support internal curing and enhance self-healing efficiency in concrete systems.

8. Recycled Industrial By-Product Aggregates

This category includes aggregates derived from industrial waste materials such as slag, fly ash, and bottom ash. Although not always classified strictly as recycled aggregates, they are widely used as sustainable alternatives in concrete.

- **Blast Furnace Slag Aggregate**: Produced from iron manufacturing, it offers high strength and durability.
- **Fly Ash Aggregate**: Used as a lightweight aggregate with good pozzolanic properties.
- **Bottom Ash Aggregate**: Derived from coal combustion, used in lightweight and non-structural concrete.

These materials improve concrete properties such as workability, durability, and resistance to chemical attack. In self-healing concrete, their pozzolanic nature can enhance the formation of healing compounds.

The classification of recycled aggregates highlights the diversity of materials that can be reused in construction. Each type—whether derived from concrete, masonry, asphalt, glass, plastic, ceramics, or industrial by-products—offers unique advantages and limitations. Their selection depends on the intended application, required performance, and environmental considerations. In the context of self-healing concrete, recycled aggregates play an even more significant role due to their ability to retain moisture, store healing agents, and support internal curing processes. While challenges such as variability, reduced strength, and quality control persist, ongoing research and technological advancements are addressing these issues. Overall, the use of different types of recycled aggregates represents a critical step toward sustainable and resilient construction practices, aligning with global efforts to reduce waste, conserve resources, and enhance infrastructure durability.

Analyse Healing Efficiency and Durability in Self-Healing Concrete

The analysis of healing efficiency and durability is a critical aspect in evaluating the performance of self-healing concrete, especially when combined with recycled aggregates. Healing efficiency refers to the ability of the material to repair cracks and restore its original properties, while durability indicates the capacity of the concrete to withstand environmental and mechanical stresses over time. Together, these parameters determine the long-term reliability and sustainability of the material in real-world applications.

Healing Efficiency in Self-Healing Concrete

Healing efficiency is typically assessed based on the extent to which cracks are sealed and the degree to which mechanical and durability properties are restored. In self-healing concrete, cracks up to a certain width—generally between 0.2 mm and 0.5 mm—can be effectively repaired depending on the healing mechanism used. The healing process may involve autogenous healing, bacterial activity, or the release of encapsulated healing agents.

Autogenous healing occurs naturally when unhydrated cement particles react with water to form additional calcium silicate hydrate (C-S-H) gel or calcium carbonate, which fills the cracks. However, its efficiency is limited to very small cracks and depends heavily on the availability of moisture. In contrast, bacterial self-healing enhances efficiency by producing calcium carbonate through microbial activity, enabling the sealing of relatively larger cracks and improving crack closure rates.

Encapsulation-based healing systems offer a more targeted approach. When cracks occur, embedded capsules rupture and release healing agents that bond and seal the damaged area. This method can restore not only impermeability but also some degree of mechanical strength. The effectiveness of these systems depends on the distribution, size, and stability of the capsules within the concrete matrix.

Influence of Recycled Aggregates on Healing Efficiency

The incorporation of recycled aggregates has a significant impact on healing efficiency. Due to their higher porosity and water absorption capacity, recycled aggregates act as internal reservoirs of moisture. This stored water is gradually released into the concrete matrix, promoting continued hydration and enhancing autogenous healing. As a result, crack-sealing efficiency may improve in recycled aggregate concrete compared to conventional concrete.

Moreover, the porous structure of recycled aggregates can serve as carriers for bacteria or healing agents in advanced self-healing systems. This enhances the distribution and activation of healing mechanisms throughout the material. However, the variability in the quality of recycled aggregates may lead to inconsistent healing performance, requiring careful selection and processing.

Durability of Self-Healing Concrete

Durability is a key performance indicator that reflects the ability of concrete to resist deterioration caused by environmental factors such as water ingress, chemical attack, freeze-thaw cycles, and corrosion of reinforcement. Self-healing concrete significantly improves durability by sealing cracks and preventing the penetration of harmful substances.

One of the primary benefits of self-healing concrete is the reduction in permeability. When cracks are healed, pathways for water and aggressive agents are blocked, thereby minimizing the risk of reinforcement corrosion and chemical degradation. This leads to a longer service life and reduced maintenance requirements.

In the presence of recycled aggregates, durability is influenced by both positive and negative factors. On one hand, the enhanced healing efficiency due to internal curing improves resistance to cracking and permeability. On the other hand, the higher porosity and weaker interfacial transition zone (ITZ) associated with recycled aggregates may reduce resistance to external stresses and environmental exposure.

Factors Affecting Healing Efficiency and Durability

Several factors influence the healing efficiency and durability of self-healing concrete with recycled aggregates:

- **Crack Width:** Smaller cracks are more easily healed than larger ones.
- **Moisture Availability:** Essential for both autogenous and bacterial healing processes.
- **Type of Healing Mechanism:** Different techniques offer varying levels of efficiency.
- **Quality of Recycled Aggregates:** Affects strength, porosity, and consistency.
- **Environmental Conditions:** Temperature, humidity, and exposure conditions impact healing performance.

Evaluation Methods

Healing efficiency and durability are evaluated using various experimental methods, including:

- Visual crack closure observation
- Water permeability and absorption tests
- Compressive and flexural strength recovery tests
- Microscopic analysis (e.g., SEM)
- Durability tests such as chloride penetration and freeze-thaw resistance

These methods provide quantitative and qualitative insights into the performance of self-healing concrete.

The analysis of healing efficiency and durability demonstrates that self-healing concrete incorporating recycled aggregates offers a promising solution for enhancing the lifespan and sustainability of concrete structures. While recycled aggregates may introduce certain challenges, their contribution to internal curing and healing processes can significantly improve crack repair efficiency. With proper material design, quality control, and optimization of healing mechanisms, it is possible to achieve a balance between durability, strength, and sustainability. Continued research in this area will further refine these materials and expand their practical applications in the construction industry.

IX. Threats

- High initial cost of self-healing materials
- Lack of standardized design guidelines
- Limited large-scale implementation
- Variability in recycled aggregate quality
- Possible reduction in compressive strength

X. Data Analysis

Studies show:

- Crack healing up to 0.2–0.5 mm in many self-healing systems
- Strength reduction of 10–30% when using recycled aggregates
- Improved durability due to reduced permeability
- Increased water absorption in recycled aggregate concrete

XI. Research Gap

Despite the growing body of literature on self-healing concrete, several critical gaps remain, particularly in the integration of recycled aggregates within such systems. Existing studies have extensively explored either self-healing mechanisms (such as microbial, chemical, and encapsulation-based healing) or the use of recycled aggregates independently; however, limited research has systematically combined these two approaches to evaluate their synergistic performance.

Firstly, there is a lack of comprehensive understanding of how recycled aggregates influence the self-healing capacity of concrete. Recycled aggregates often introduce higher porosity and microcracks, which may either enhance healing by providing pathways for healing agents or hinder it by reducing mechanical strength. This dual effect is not yet fully quantified or standardized across different mix designs.

Secondly, insufficient experimental data exist on the long-term durability and healing efficiency of self-healing concrete incorporating recycled aggregates under varied environmental conditions. Most studies focus on short-term laboratory performance, leaving a gap in real-world applicability and lifecycle assessment.

Additionally, there is limited comparative analysis of different self-healing techniques when used in conjunction with recycled aggregates. The effectiveness of methods such as bacterial healing, crystalline admixtures, and encapsulated agents in recycled aggregate concrete remains underexplored. Moreover, the economic feasibility and scalability of combining self-healing technologies with recycled materials have not been adequately addressed. While both approaches individually promote sustainability, their combined cost-benefit performance is still unclear. Finally, standardized testing methods and performance indicators for evaluating healing efficiency in recycled aggregate-based self-healing concrete are lacking, leading to inconsistencies in reported results and difficulty in benchmarking. Therefore, further research is needed to systematically investigate the interaction between self-healing mechanisms and recycled aggregates, optimize material design, and establish reliable performance metrics to support large-scale practical implementation.

XII. Key Findings

- Self-healing concrete significantly enhances durability
- Recycled aggregates contribute to sustainability
- Healing efficiency depends on crack width and method used
- Trade-off exists between strength and eco-friendliness

XIII. Advantage

- Reduces maintenance and repair costs
- Extends structural lifespan
- Eco-friendly and sustainable
- Decreases landfill waste
- Improves crack resistance

XIV. Disadvantage

- High initial cost
- Limited availability of technology
- Reduced mechanical strength in some cases
- Complex manufacturing process
- Lack of awareness and standards

XV. Comparison

Table 1: Conventional Concrete Vs Self-Healing Concrete with Recycled Aggregate

Parameter	Conventional Concrete	Self-Healing Concrete with Recycled Aggregate
Durability	Moderate	High
Maintenance	Frequent	Minimal
Cost	Low initial	High initial, low long-term
Sustainability	Low	High
Crack Repair	Manual	Automatic

Table 2: Comparison of Type of Recycled Aggregate

Type of Recycled Aggregate	Source Material	Key Properties	Advantages	Disadvantages	Common Applications
Recycled Concrete Aggregate (RCA)	**Demolished concrete (buildings, pavements)**	**Moderate strength, rough texture, high water absorption**	**Widely available, good bonding,**	**Reduced strength due to adhered mortar**	**Structural concrete, road base, pavements**

Type of Recycled Aggregate	Source Material	Key Properties	Advantages	Disadvantages	Common Applications
			supports internal curing		
Recycled Masonry Aggregate (RMA)	Bricks, tiles, ceramics	Lightweight, highly porous, low strength	Good thermal insulation, enhances water retention	High variability, low durability	Non-structural concrete, blocks, fillers
Mixed Recycled Aggregate (MRA)	Combination of concrete, masonry, asphalt, etc.	Heterogeneous, variable properties	Cost-effective, reduces mixed waste	Inconsistent quality, difficult quality control	Sub-base layers, road construction
Recycled Asphalt Aggregate (RAA)	Reclaimed asphalt pavement	Flexible, bitumen-coated particles	Good for flexible pavements, reduces waste	Poor bonding with cement, limited use in concrete	Asphalt roads, pavement layers
Recycled Glass Aggregate (RGA)	Crushed waste glass	Smooth texture, reactive silica content	Aesthetic appeal, reduces landfill waste	Risk of alkali-silica reaction (ASR)	Decorative concrete, fine aggregate replacement
Recycled Plastic Aggregate (RPA)	Waste plastics (PET, PE, PP)	Lightweight, low density, non-absorbent	Corrosion-resistant, eco-friendly	Low strength, weak bonding with cement	Lightweight concrete, insulation materials
Recycled Ceramic Aggregate	Ceramic waste (tiles, sanitary ware)	Hard, brittle, porous	Good durability, supports internal curing	Brittle behavior, moderate water absorption	Paving blocks, decorative concrete
Industrial By-Product Aggregates	Slag, fly ash, bottom ash	Variable density, pozzolanic properties	Improves durability, sustainable	Requires processing, variable composition	Structural and lightweight concrete

XVI. Conclusion

Self-healing concrete using recycled aggregates represents a significant advancement in the field of sustainable construction materials, combining innovation with environmental responsibility. This study has examined the fundamental concept of self-healing concrete, highlighting its ability to autonomously repair cracks through mechanisms such as autogenous healing, bacterial activity, and encapsulated healing agents. These techniques contribute to enhancing the durability and service life of concrete structures, reducing the need for frequent maintenance and repairs.

The role of recycled aggregates has also been critically evaluated, revealing both their potential and associated challenges. Recycled aggregates, derived from construction and demolition waste, play an important role in promoting sustainability by conserving natural resources and minimizing landfill waste. Their higher absorption capacity and porosity can support internal curing, which may positively influence the self-healing process. However, these same properties can also lead to reduced mechanical strength and variability in performance, making careful material selection and processing essential. The analysis of healing efficiency and durability indicates that self-healing concrete can effectively seal small cracks and improve resistance to water penetration and chemical attack. The extent of healing largely depends on factors such as crack width, type of healing mechanism, and environmental conditions. Despite some limitations, the overall performance shows promising improvements compared to conventional concrete.

Furthermore, the study has identified several advantages, including enhanced durability, reduced maintenance costs, and environmental benefits. At the same time, limitations such as high initial costs, lack of standardization, and limited large-scale applications remain key concerns that need to be addressed. Looking ahead, there are considerable opportunities for future research. Efforts should focus on improving the mechanical properties of recycled aggregate concrete, optimizing healing techniques, and developing cost-effective and scalable solutions. With continued advancements, self-healing concrete using recycled aggregates has the potential to revolutionize the construction industry by offering durable, eco-friendly, and resilient infrastructure solutions.

XVII. References

- M. C. Limbachiya, T. Leelawat, and R. K. Dhir, “Use of recycled concrete aggregate in high-strength concrete,” Mater. Struct., vol. 33, no. 9, pp. 574–580, 2000.
- H.-J. Chen, T. Yen, and K.-H. Chen, “Use of building rubbles as recycled aggregates,” Cem. Concr. Res., vol. 33, no. 1, pp. 125–132, 2003.
- Jonkers, H. M. (2010). Bacteria-based self-healing concrete
- Neville, A. M. (2011). *Properties of Concrete*
- Mehta, P. K., & Monteiro, P. J. M. (2014). *Concrete: Microstructure, Properties, and Materials*
- Ashwija.K.C., and Jayaprakash Narayan.K.S" Experimental Study on The Strength Variation of Concrete Using Bacteria" International Journal of Advanced Biotechnology and Research ISSN 0976-2612, Vol 3, Issue 1, 2012,pp 541-544
- Sudhir P.Patel, Ganesh S.Ingle, Prashanth D Sathe, "Recycled Coarse Aggregates" International Journal of Advanced Technology in Civil Engineering, ISSN:2231–5721, Volume-2, Issue-1, 2013.
- Singh, B., et al. (2015). Utilization of recycled aggregates in concrete
- Navdeep Singh, S.P. Singh, Evaluating the performance of self-compacting concretes made with recycled coarse and fine aggregates using non-destructive testing techniques, Construction and Building Materials, Volume 181,2018,Pages 73-84,ISSN 0950-0618,https://doi.org/10.1016/j.conbuildmat.2018.06.039. (https://www.sciencedirect.com/science/article/pii/S0950061818314296)
- Neha Rupawate, Shweta Yadav, Mukul Patil "Experimental Study on the Behaviour of Concrete by Using Recycled Aggregates and Enhancing Its Self Healing Properties by Using Bacteria" International Journal of Scientific Research in Science, Engineering and Technology (IJSRSET), Print ISSN : 2395-1990, Online ISSN : 2394-4099, Volume 4, Issue 6, pp.15-23, January-February-2018.
- Mishra, O., & Singh, S. P. (2019). An overview of microstructural and material properties of ultra-high-performance concrete. *Journal of Sustainable Cement-Based Materials*, *8*(2), 97–143. https://doi.org/10.1080/21650373.2018.1564398
- Tayeh, Bassam & Al Saffar, Doha & Alyousef, Rayed. (2020). The Utilization of Recycled Aggregate in High Performance Concrete: A Review. Journal of Materials Research and Technology. 9. 8469-8481. 10.1016/j.jmrt.2020.05.126.
- AKBAS, MERVE, Utilization of Recycled Concrete Aggregates for Developing High-Performance and Durable Flexible Pavements. Available at SSRN: https://ssrn.com/abstract=4487546 or http://dx.doi.org/10.2139/ssrn.4487546
- Yue Liu, Yan Zhuge, Wei Fan, Weiwei Duan, Lei Wang,Recycling industrial wastes into self-healing concrete: A review, Environmental Research,Volume 214, Part 4,2022,113975,ISSN 00139351 , https://doi.org/ 10.1016/j. envres.2022.11 3975. (https://www.sciencedirect.com/science/article/pii/S0013935122013020)
- C. C. Bungau, T. Bungau, I. F. Prada, and M. F. Prada, “Green Buildings as a Necessity for Sustainable Environment Development: Dilemmas and Challenges,” Sustain., vol. 14, no. 20, p. 13121, 2022, doi: 10.3390/su142013121.
- ACI Committee Reports on Sustainable Concrete (https://www.concrete.org/getinvolved/committees/directoryofcommittees/acommitteehome.aspx?committee_code=C0013000)
- Relevant journal articles from *Construction and Building Materials* 2026,vol 520
- IS Codes for Concrete Design and Sustainability
- Kanaujia, S. C., Khan, Z. R., Ahmad, S. A., & Singh, V. (2025). Recycled Concrete Aggregates from Construction and Demolition Waste: A Systematic and Critical Review of a Sustainable Construction Material. *International Journal of Environment, Engineering and Education*, *7*(2), 84-96.
- Shukla, B. K., Yadav, H., Singh, S., Verma, S., Shukla, A. K., & Sharma, C. (2025). Sustainable Engineering of Recycled Aggregate Concrete: Structural Performance and Environmental Benefits Under Circular Economy Frameworks. *Construction Materials*, *5*(3), 67.

- Panghal, H., Chaudhary, S., & Kumar, A. (2025). Enhancing sustainable concrete performance: dual treatment of recycled coarse aggregates for improved strength and durability. *European Journal of Environmental and Civil Engineering*, *29*(15), 3225-3256.
- A. Morgado and P. Hugues, "Tracking Cement," International Energy Agency (IEA), 2023. https://www.iea.org/energy-system/industry/cement (accessed Jun. 30, 2025).
- Alibeigibeni, A., Stochino, F., Zucca, M., & Gayarre, F. L. (2025). Enhancing concrete sustainability: a critical review of the performance of recycled concrete aggregates (RCAs) in structural concrete. *Buildings*, *15*(8), 1361.
- Bhardwaj, B. B., Sadasivan, S., Singh, S., & Kumari, M. (2026). Tolerance Level of Bricks in Recycled Concrete Aggregates. *Transportation Research Record*, *2680*(3), 119-138.
- Singh, S., & Uppaluri, R. V. (2026). Nano-Engineered Recycled Aggregate Concrete: Enhancing Strength and Durability through Nanosilica and Activated Carbon Integration. *Arabian Journal for Science and Engineering*, 1-15.
- Chaitanya, B. K., Madhavi, Y., Venkatesh, C., Durga, C. S. S., Gowd, S. C., & Mitikie, B. B. (2026). Multi-scale performance, life-cycle and economic assessment of blended concrete using recycled coarse aggregates. *Scientific Reports*.
- Aggarwal, A., Goel, G., & Singh, S. K. (2026). Creating Circularity in the Production of Sustainable Concrete by Unlocking the Potential Applications of Steel Slags as Coarse Aggregates. *Journal of Materials in Civil Engineering*, *38*(5), 03126002.
- Anand, P., Sinha, A. K., Rajhans, P., & Bhowmik, P. N. (2025). Enhancing concrete sustainability: Synergistic effects of individual and dual treatments on recycled coarse aggregate from construction and demolition waste. *Journal of Structural Design and Construction Practice*, *30*(3), 04025055.